Chapter 2: The Past and Present Carbon Cycle

Chapter 1 reviewed the two overarching scientific questions that the Carbon Cycle Science Plan (CCSP) is designed to address. This chapter turns more focused attention to the first of these two questions:

What has happened to the CO_2 that has already been emitted through human activities (anthropogenic carbon dioxide)?

Carbon cycle research relating to climate change fundamentally concerns three large scientific issues. The first is the natural partitioning of carbon among the "mobile" reservoirs—the ocean,atmosphere,and soil and terrestrial biosphere—partitioning that is influenced itself by climate change. The second issue is the redistribution of fossil fuel CO_2 within those same three reservoirs,and assessments of proposals to prevent emissions or sequester carbon through new technologies. The third issue concerns transfers between the terrestrial biosphere and the atmosphere induced by other human activities such as forest clearing and regrowth,the management of agricultural soils,and the feedback potential of anthropogenically driven changes in atmospheric chemistry and climate to alter these transfer rates.

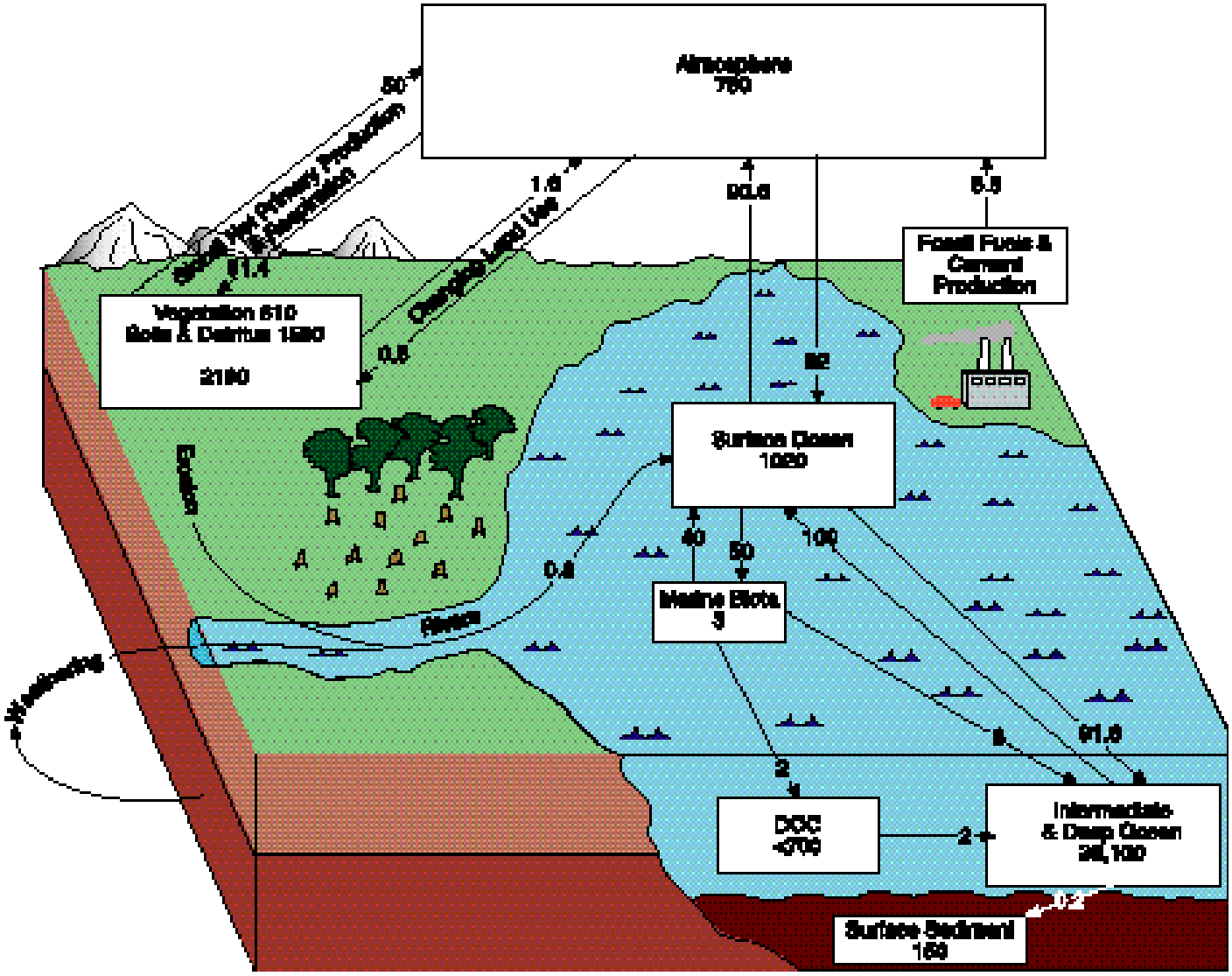
Historical changes in the quasi–steady state of the carbon system are clearly reflected in ice core and isotopic records,which also record the unprecedented changes caused by anthropogenic CO_2 emissions (Raynaud et al. 1993). The globally averaged atmospheric CO_2 mole fraction is now over 365 μmol/mol (or parts per million, ppm)—higher than it has been for hundreds of thousands of years. Atmospheric concentrations of CO_2 had remained between 270 and 290 ppm during the last several thousand years,but rose suddenly to the present level during the second half of the 20th century. This increase is coincident with the rapid rise of fossil fuel burning.

The modern rate of atmospheric CO_2 increase is accurately known from contemporary direct atmospheric measurements as well as from air stored in ice and firn (Battle et al.1996,Etheridge et al.1996). The Intergovernmental Panel on Climate Change (IPCC) assessment has summarized the state of scientific knowledge in this area (Schimel et al.1995). During the decade of the 1980s,the rate of increase in the atmosphere was 3.3 ± 0.2 billions of metric tons (also called gigatons) of carbon per year (Gt C/yr). The next best-known piece of the puzzle is the rate of fossil fuel emissions,which was 5.5 ± 0.5 Gt C/yr during the 1980s (Marland et al.1994). Thus,it is clear that on average a large fraction of the emitted CO_2 did not remain in the atmosphere. Conservation of mass implies that the missing emissions must have entered the ocean,the terrestrial biosphere,or both. The ocean carbon sink is the best known of these two remaining components of the carbon budget. According to the IPCC,the ocean absorbed 2.0 ± 0.8 Gt C/yr. This finding suggests that the global net terrestrial biosphere sink was only 0.2 ± 1.0 Gt C/yr. However, the estimated loss of carbon from the terrestrial biosphere due to deforestation is estimated to have been 1.6 ± 1.0 Gt C/yr. Thus,there must have been a compensatory storage of carbon in the terrestrial biosphere of 1.8 ± 1.6 Gt C/yr. The latter figure largely compensates for the land use source,so that the global net storage in terrestrial ecosystems was close to zero.

It has not been easy to arrive at these estimates. Regarding ocean uptake,if the CO_2 entering the ocean were mixed homogeneously, the cumulative increase in the total carbon content after 10 years at the rate of 2 Gt C/yr would only be 1.2 μmol/kg. This equals the detection limit of the currently best analytical techniques. Most of the CO_2 has been added to the upper few hundred meters,however. The signal is therefore detectable,but it must be extracted from large natural variations of up to about one to two hundred μmol C/kg. For this reason, until very recently, ocean uptake has been estimated using models whose parameters are calibrated against the penetration into the ocean of other tracers such as ^{14}C and tritium from nuclear tests,and chlorofluorocarbons.

Estimates of terrestrial carbon loss have been based on surveys of land use and changes in land use, above- and below-ground average carbon densities for ecosystem classes,and models of the development of carbon storage after disturbance,under human management,and during succession (e.g.,Houghton et al.1987). These assessments have varied greatly, as reflected in the range for tropical biomass destruction assessed by the IPCC to be 1.6 ± 1.0 Gt C/yr. Part of the problem in this evaluation is the great heterogeneity of carbon content on small spatial scales. But also,surveys have been difficult to compare because of incompatible definitions,different counting methods,the treatment of secondary forest growth,and similar reasons.

Estimates of terrestrial carbon uptake have been obtained from mass balance considerations such as those described above,which give a total uptake of 1.8 ± 1.6 Gt C/yr. Other estimates come from direct observations of forest carbon inventory changes (0.9 Gt C/yr in the Northern Hemisphere),models of NO_x fertilization (0.6 to 0.9 Gt C/yr),and CO_2 fertilization (0.5 to 2.0 Gt C/yr) (Schimel et al.1995). There are strong indications that there is a large uptake in the Northern Hemisphere,but



The principal anthropogenic carbon fluxes, against the background of some of the main 'background'natural fluxes. The results are updated from the 1995 IPCC report and Schimel (1995) with updates from Sarmiento and Sundquist (1992) and Hansell and Carlson (1998).Fluxes shown are estimated averages for the decade of the 1980s. Where unbalanced fluxes are indicated (global primary production and respiration, land use and air-sea gas exchange) the imbalance reflects the anthropogenic fluxes. Note that this figure shows decadal average fluxes and we now know these fluxes to be quite variable from year to year.

the location,magnitude,and mechanisms of this uptake are poorly understood.

The following three sections summarize recent progress on the most uncertain components of the perturbations to the global carbon budget: (1) the terrestrial carbon sink,(2) the ocean sink,and (3) the land use source. Each section is concluded with a proposed major near-term (5 to 10 year) research initiative that will address the most compelling scientific issues identified, and which is also scientifically feasible and cost-effective.

The Terrestrial Carbon Sink

Perhaps the biggest recent change in thinking about the terrestrial sink has been that earlier estimates of enormous carbon losses from terrestrial ecosystems (Bolin 1977,Woodwell 1978) have given way to the idea that the terrestrial biosphere has been close to neutral with respect to carbon storage during the last decades. The observed destruction of forests appears to have been roughly compensated for by mechanisms of enhanced carbon uptake. Eight independent lines of evidence support this view:

1. The overall carbon budget estimated from the observed atmospheric increase and ocean uptake estimates using calibrated ocean models requires modest terrestrial uptake to satisfy mass balance (Bacastow and Keeling 1973,Oeschger et al.1975).
2. The smaller than expected north-south gradient of atmospheric CO_2, combined with data on the partial pressure of CO_2 in ocean surface waters,suggests that there is a large terrestrial CO_2 sink at temperate latitudes in the Northern Hemisphere (Tans et al. 1990). The sink compensates for, or is larger than, the estimated rate of carbon loss due to deforestation in the tropics.
3. The atmospheric ratio of oxygen to nitrogen has been declining due to the consumption of oxygen by fossil fuel burning. The ratio is decreasing as oxygen use is required by this fossil fuel burning,though perhaps slightly more slowly, indicating that there is no major net O_2 sink other than fossil fuel burning. There may even be a small net source,which would suggest that biological fixation of CO_2 may exceed rates of remineralization of organic matter (Battle et al.1996, Keeling et al.1996).
4. The existence of a large terrestrial sink at northern latitudes is supported by $^{13}C/^{12}C$ ratio measurements in atmospheric CO_2 (Ciais et al.1995a) and by measurements of the oxygen/nitrogen ratio (O_2/N_2) (Keeling et al.1996). At northern latitudes the $^{13}C/^{12}C$ and O_2/N_2 ratios are higher (relative to the Southern Hemisphere) than expected from fossil fuel burning alone. This suggests net uptake by photosynthesis,which (1) discriminates against uptake of ^{13}C relative to ^{12}C, leaving the atmosphere enriched in ^{13}C,and (2) produces O_2, enhancing the O_2/N_2 ratio.
5. A new technique is eddy covariance,which can measure vertical transport in a turbulent atmosphere. Flux measurements obtained by this technique in different ecosystems have demonstrated the ability of some forests to act as significant net sinks for atmospheric CO_2 (Wofsy et al.1993,Baldocchi et al.1996). However, the number of such measurements that is available is too limited to draw any strong conclusions.
6. The increase in amplitude of the seasonal cycle of atmospheric CO_2, and especially the earlier onset of the summer photosynthetic drawdown,is consistent with net uptake by temperate land ecosystems (Myneni et al.1997,Randerson et al.1997).
7. Recent forestry surveys in various regions of the Northern Hemisphere also tend to indicate net carbon uptake,but not as large as the atmospheric data seem to imply (Dixon et al.1994).
8. During earlier decades (1970–1990) the measured change in the oceanic $^{13}C/^{12}C$ ratio indicates relatively little net uptake by the terrestrial biosphere when analyzed in the context of changes in atmospheric concentrations (Quay et al.1992).

The storage of organic carbon in terrestrial sediments may be much more important than previously recognized (Stallard 1998). Carbon storage through erosion may sequester carbon if significant amounts of eroded carbon are stored in sediments where they will decompose slowly, and if regrowth of vegetation on eroded lands replaces the lost carbon. This sink,combined with expansion of rice agriculture and postulated net storage of carbon in rice paddy soils,could amount globally to 0.6-1.5 Gt C/yr (Stallard 1998).

It is noteworthy that five of the above arguments are based entirely or partly on the atmospheric measurement of fluxes,either directly or as deduced from spatial patterns of the concentration of gaseous species. The first argument is based on a global mass balance involving the ocean,and the first of the flux arguments makes use of air-sea fluxes. Estimates of aboveground terrestrial biomass are being made routinely, but two-thirds of the global terrestrial carbon is in soils,and it has been hard to obtain accurate inventories,let alone temporal change data for this pool. It is encouraging that the evidence for terrestrial sinks is internally consistent because each of the approaches has its own problems,to be briefly discussed next.

Interpreting observations of the CO_2 mole fraction in terms of surface sources and sinks requires atmospheric transport models that portray large-scale circulation

accurately, and that also parameterize subgrid-scale mixing correctly. The recent atmospheric transport model comparison study (TRANSCOM) exercises show that significant improvement in both respects is sorely needed,and that the atmospheric boundary layer is of particular importance (Law et al.1996,Denning et al.1999). Because the atmospheric signature of low-latitude sources is weak due to vigorous vertical mixing,and because there are no applicable observations in some important areas (such as tropical forests),the models currently work roughly as follows. Sources and sinks are derived from observed concentration patterns with some degree of confidence for the temperate and high latitudes,and those for low latitudes then follow essentially from global mass conservation. Calibrations of certain aspects of the transport with other tracers with "known"sources,such as CFCs, ^{85}Kr, or SF_6, are useful,but fail in that the strong diurnal and seasonal cycles of CO_2 sources are not included,and also because these tracers have strong sources in the tropics.

The interpretation of the isotopic data is subject to substantial uncertainty. The main source of error is the contribution of purely isotopic exchange,often called the isotopic disequilibrium flux,which may occur with or without an accompanying net exchange of total carbon (Tans et al.1993). A better determination of the rate of air-sea gas exchange is especially important to pin down the isotopic disequilibrium flux between the ocean and atmosphere. The isotopic disequilibrium between the atmosphere and the terrestrial biosphere depends on the average age of the respiratory carbon flux,which should be better known as well. This age is important because older biomass was fixed during times that the atmosphere was less depleted in ^{13}C than today. In interpreting atmospheric $^{13}C/^{12}C$ trends, relatively small uncertainties in isotopic disequilibrium between the atmosphere and ocean translate into large uncertainties in the partitioning of the total sink between ocean and land (e.g.,an uncertainty of only 0.1 per mil,or parts per thousand,in isotopic disequilibrium gives an uncertainty of 0.5 Gt C in partitioning). Furthermore,the isotopic signature of terrestrial primary productivity, strongly influenced by the relative proportions of the C3 and C4 photosynthetic pathways,needs to be better defined.(Fung and al.1997,Lloyd and Farquahar 1994). The isotopic fractionation during C4 photosynthesis is not much different from that of air-sea exchange.

The atmospheric oxygen budget may be subject to uncertainties concerning decadal variations in the ventilation of deeper, oxygen-poor waters of the ocean. It is reassuring that two completely different analytical techniques give similar results (Bender et al.1994, Keeling and Shertz 1992).

The new micrometeorological (eddy-covariance) flux measurement methods have been developed to measure ecosystem exchange of trace gases on a spatial scale of hundreds of meters (Wofsy et al.1993,Baldocchi et al. 1996,Goulden et al.1998). There is also a network of about 10 U.S.Department of Agriculture (USDA) Agricultural Research Service grassland sites (tallgrass, mixed grass,shortgrass steppe,intermountain,and shrublands) equipped with Bowen Ratio/Energy Balance (BR) towers that are monitoring CO_2 and H_2O fluxes. In grasslands,BR systems work well and are less relatively expensive. Such measurements are used in conjunction with known disturbance history, and with climatic,plant physiological,ecological,and soil data,to investigate mechanisms responsible for the uptake or loss of carbon for whole forest ecosystems,including soils.

The manageable spatial scale facilitates the search for flux mechanisms,but makes it necessary to test extrapolations to regional scales with other methods. Relationships between fluxes and climatic variables have been found (Goulden et al.1996,Goulden et al.1998). When turbulence is well developed,often during the day, the eddy-covariance method is well demonstrated,but at night under stable conditions,the measurements are less reliable and heterotrophic respiratory fluxes (fluxes from non-photosynthetic organisms) may be underestimated. This problem can be partially circumvented by selecting measurement times when conditions for the method are favorable,although this introduces the danger of aliasing, or obtaining biased data because of non-representative sampling. An explicit quantification of the spatial error associated with the measurement of net ecosystem production (NEP) by the eddy flux method will allow a quantitatively defensible scaling-up from local to regional analyses of NEP. This achievement will require replication of eddy flux towers at both local and regional scales. The number and spacing of such towers is a topic for research,but techniques are available that can be applied to the task (e.g.,Harrison and Luther 1990).

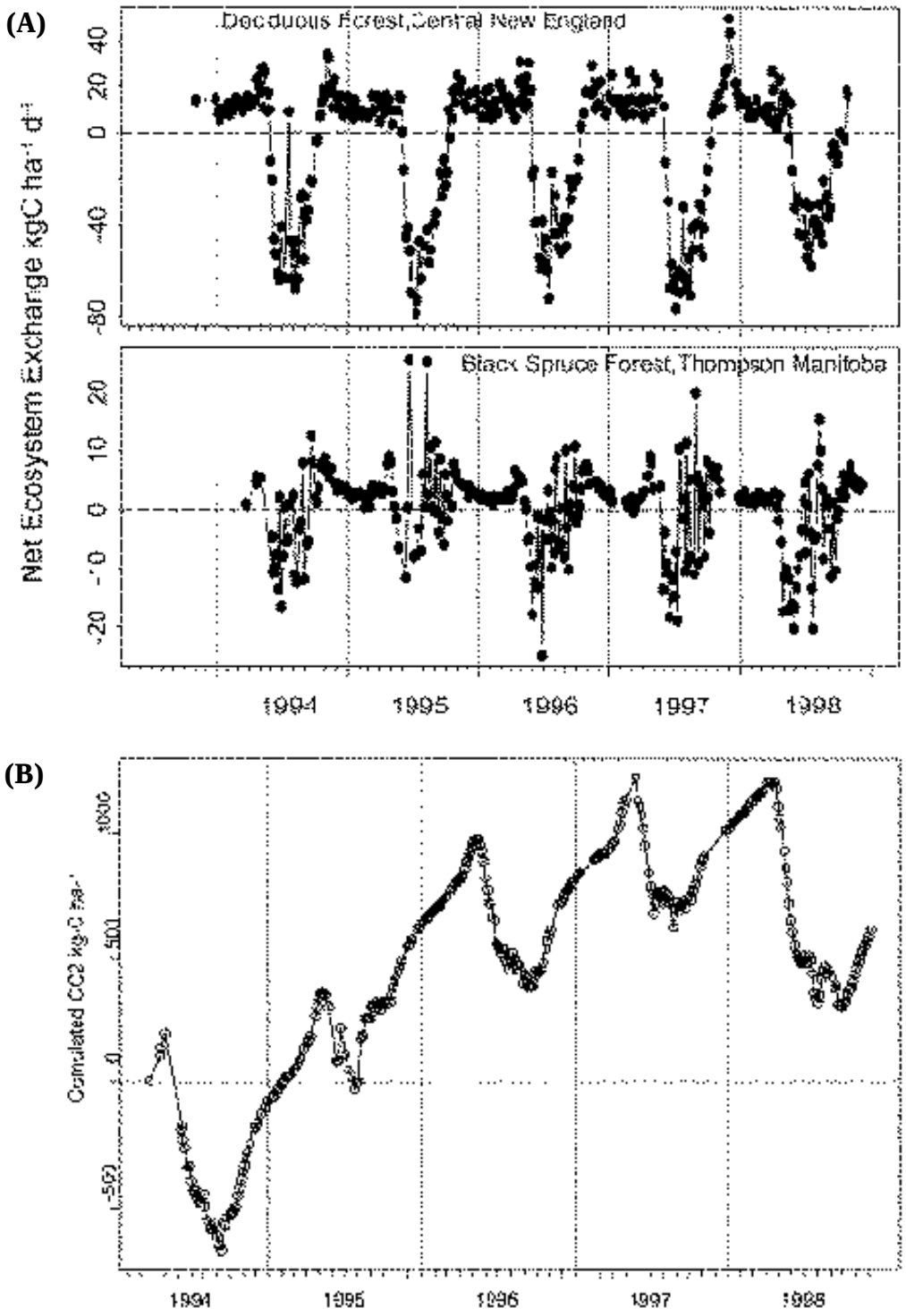
A central theme of research on the terrestrial carbon sink over the last decade can be formulated as the following hypothesis:

Hypothesis 1: sink for anthropogenic	There is a large terrestrial CO_2 in the Northern Hemisphere.

This hypothesis is known by the term the Northern Hemisphere Terrestrial Carbon Sink or "Northern Land Sink."

The suggestion that there is such a carbon sink is strongly supported by a wide range of observations,data analysis,and modeling studies,many of which have been discussed above. The magnitude of this sink was estimated to be on the order of 1.5 + 1.0 Gt C/yr for 1980-1989 (Schimel et al.1996),and as having increased to >2.5 Gt C/yr over the last decade,making it a major contributor to

(A) Daily net ecosystem exchange for Harvard Forest, Central New England (top) and the BOREAS site, Manitoba, Canada (bottom). These data are illustrative of the rich information to be gained from flux towers. Both forest sites show the pattern of carbon exchange throughout the year, with carbon uptake occurring during the growing season (negative values) and release during the winter (positive values). Differences between sites can also be noted: the growing season starts earlier at the BOREAS site, yet the forest there is less efficient overall at storing carbon. Data from towers can also be analyzed in conjunction with temperature and precipitation patterns, for example, to determine the long-term responses of major ecosystems to climate variability.
(B) Overall, the BOREAS site was a net source of carbon to the atmosphere during 1994 to 1998, despite a longer growing season than average. This result is partially due to the release of carbon from cold soils starting earlier in the year, around August, and persisting throughout the winter months.



perturbations of the carbon budget. However, in addition to the large uncertainty in the magnitude of this sink, its location and interannual variability, and the mechanisms that cause it are all highly speculative.

One important issue to address in this context is the role played by CO_2 and nitrogen fertilization in the current carbon balance.

These two types of fertilization may stimulate biogenic uptake of carbon, thus providing a carbon sink. They are generally believed to be most important at mid-northern latitudes (Schimel et al. 1996), but these mechanisms must be further quantified and their possible future roles assessed. Ecosystem manipulations, including studies with elevated CO_2 and nitrogen additions, and consideration of a range of potentially interacting factors, will provide insights into physiological, ecological, and biogeochemical processes underlying the carbon storage in the terrestrial biosphere. These same points apply to controlled applications of ozone. Projects investigating these processes are coordinated by the Global Change and Terrestrial Ecosystems (GCTE) project of the International Geosphere-Biosphere (IGBP) Program. The results from these experiments will need to be extrapolated from the experimental scale to larger regions, requiring understanding of the scale-dependence of the processes and their interactions.

Extending the results of these experiments from the local to regional and global scales will require four components. First, the experiments must be designed to provide access to the underlying mechanisms that control the scaling. Second, the experiments must be repeated in enough ecosystems to capture the full range of mechanisms. Third, the regions where the responses are estimated must be sufficiently characterized to support the extrapolation. And fourth, the models used for the scaling must be robust. The terrestrial biosphere is too heterogeneous to be characterized by simple extrapolation of a reasonable number of experiments, but the processes that regulate it are uniform enough to be effectively handled in mechanistic models.

Another fundamental issue in this area is how carbon storage is affected by changes in land use, disturbance, and vegetation structure and composition.

Carbon storage in vegetation is being continually altered by land use and disturbance (e.g., fires) and with the recovery of vegetation from historic land use. In addition, the competitive relationships among species and their interdependence are changing owing to multiple causes, climate change among them. A change from grassland to forest, for example, would certainly change carbon storage. Changes in vegetation assemblages are likely to be important drivers for carbon storage or release on decadal and longer time scales. The development of dynamic global vegetation models (DGVMs) is beginning to accelerate, and they will likely become important tools in understanding the future carbon cycle.

The development of measurement techniques and methods of data analysis have placed us in a position to propose a major new near-term CCSP initiative with the following goal:

> Goal 1: Establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

Large carbon sinks have been hypothesized to be associated with a variety of terrestrial phenomena (for example, greater erosion and sediment deposition, land use changes, CO_2 fertilization, and length of the growing season). Clearly, additional observations and improved models of terrestrial processes are needed.

Such terrestrial studies cannot be interpreted in isolation. The Northern Land Sink hypothesis directly suggests additional linked hypotheses and observations. As research on land clarifies the distribution of particular hypothesized sources and sinks, parallel improvements will be required in the temporal and spatial resolution of atmospheric and oceanic observations and models. For example, a direct corollary of the Northern Land Sink hypothesis is the hypothesis that there is a large oceanic carbon sink in the Southern Hemisphere. This sink is hypothesized because the global CO_2 budget requires a large ocean sink somewhere, and Northern Hemisphere ocean CO_2 uptake appears to be relatively small based on the atmospheric ^{13}C and ocean surface pCO_2 (partial pressure of CO_2) measurements (Tans et al. 1990). These are the same measurements and arguments that led to the hypothesis of the Northern Land Sink.

The Ocean Carbon Sink

The total capacity of the ocean to dissolve anthropogenic CO_2 is mainly a chemical property and can be calculated by considering the appropriate chemical equilibria. The primary challenge to current understanding of the ocean carbon sink is in estimating the rate at which anthropogenic CO_2 dissolves in the ocean. It is necessary to know the present rate of dissolution and how climate change and changes in the biological pump will affect the uptake rate and ultimate capacity in the future. A separate, but also important, problem is to determine the spatial distribution of air-sea CO_2 fluxes, a factor that is a major constraint on inverse modeling analyses such as those discussed in the previous section. Each of these issues is discussed in turn, beginning with present knowledge of the rate of ocean carbon uptake and the spatial distribution of carbon sources and sinks. Chapter 3 addi-

tionally discusses how climate change and related changes in the biological pump might affect the rate of uptake in the future.

Ocean carbon uptake has been estimated by considering the change in carbon inventory through time, the magnitude of the air-sea CO_2 flux, and the magnitude of carbon transport within the ocean. The estimates used by the IPCC in constructing global carbon budgets are based primarily on inventory calculations using ocean circulation models calibrated or validated with tracer observations (e.g., bomb radiocarbon; see Schimel et al. 1996). The magnitude of these estimates has remained consistent over almost three decades of continuous testing with new models and tracer data. Nevertheless, the estimates are typically reported as having an uncertainty of ± 40 percent. The large uncertainty reflects the fact that tracer measurements are imperfect analogs for fossil fuel CO_2 and have been relatively sparse until quite recently.

Further, ocean models have limitations in their representations of ocean circulation and mixing. An important goal of research over the last decade has thus been to expand the tracer data set and improve ocean carbon models. The skill of ocean carbon cycle simulations is directly linked with improving models of the physical transport of the underlying ocean general circulation. Considerable success has been achieved in the last decade through better parameterization of mesoscale eddy mixing processes (Gent et al. 1995).

Additionally, there has been a major effort to develop methods and obtain measurements to assess the oceanic uptake directly or indirectly from dissolved inorganic carbon (DIC) observations.

One of the most important advances has been the acquisition of a new global data set of ocean tracer and carbon system observations of unprecedented accuracy through the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS). The tracer measurements, together with the rapid improvement of ocean circulation models based on these and other WOCE observations, are expected to lead to improved model uptake estimates. DIC data sets accurate to 1 to 2 mmol/kg, which is equivalent to 1 to 2 years' uptake of anthropogenic CO_2 in near-surface waters, are now available for hydrographic transects representing most of the world's ocean. The $^{13}C/^{12}C$ of DIC was measured on every sample collected for Accelerator Mass Spectrometry (AMS) ^{14}C measurement during WOCE, which yields the first oceanwide high-quality $^{13}C/^{12}C$ data set (±0.03 parts per thousand). These new data sets are already significantly improving knowledge of the distribution of inorganic carbon in the ocean.

A parallel occurrence has been the development of methods to estimate the oceanic uptake of carbon by direct analysis of the DIC observations. Three complementary methods have been proposed in order to constrain (or set the estimated outside boundaries of) the oceanic uptake of anthropogenic carbon directly from ocean data: (1) repeat or time-series observations of water column DIC to measure the current rate of change of the DIC inventory; (2) "preformed CO_2" methods to calculate the integral change of the DIC inventory from the pre-industrial period to the present; and (3) air-sea CO_2 flux methods to measure the present global net flux into the ocean.

One of the most important needs is to gain a better understanding of the spatial patterns of surface ocean CO_2 concentrations and their variability. Seasonal and interannual variability of CO_2 concentrations in the surface ocean are one to two orders of magnitude greater than their annual increase due to uptake of anthropogenic carbon (e.g., Bates et al. 1996, Winn et al. 1994). Because the signal to be detected is much smaller than this variability, it takes a decade or longer to begin to see anthropogenic trends. In addition, the seasonal and interannual variability in CO_2 concentration gives information on how the carbon cycle functions, and can be used in conjunction with other methods to help understand regional and global patterns of carbon uptake. A very promising development of the last decade is new instrumentation that will make it possible to measure pCO_2 (DeGrandpre et al. 1995, Friederich et al. 1995, Goyet et al. 1992, Merlivat and Brault 1995) and other properties from moorings. The CCSP envisions that moorings with these capabilities will allow establishment of many more time-series stations at feasible cost in otherwise remote locations.

An alternative to long-term measurements is to use methods of analyzing the data that permit identifying the anthropogenic carbon component within the huge background signal and variability that arises from seasonal and interannual change. The "preformed CO_2" method uses the correlation of data on carbon, nutrients, oxygen, and physical variables to separate natural variability from changes due to uptake of anthropogenic CO_2 (see Gruber et al. 1996). In a second method, multiple linear regression coefficients are calculated for carbon versus other variables (Wallace et al. 1995). These coefficients are used to correct for the natural variability between measurements made at two different times, thereby isolating the change due to addition of anthropogenic carbon. The two methods are somewhat independent and address different time scales. The preformed CO_2 method gives an estimate of the oceanic uptake of anthropogenic CO_2 since pre-industrial times; the multiple linear regression method has been applied to estimate the increase in oceanic CO_2 concentration between the Geochemical Ocean Sections program (GEOSECS) expeditions and WOCE/JGOFS, spaced about two decades apart (Wallace et al. 1995). Syntheses of Atlantic Ocean (Gruber 1998) and Indian Ocean (Sabine et al. 1999) DIC data from WOCE/JGOFS, analyzed

by the preformed CO_2 method,show large regional discrepancies between observed and modeled penetration of anthropogenic carbon. It is already clear that the observed penetration of anthropogenic CO_2 can provide, through detailed comparison with models,the basis and impetus for improving models of oceanic CO_2 uptake.

The flux of carbon between surface waters and the atmosphere can also be constrained using data of the partial pressure difference between the air and the water, ΔpCO_2, combined with estimates of the gas exchange coefficient (Takahashi et al.1997). Of course,this flux includes both a natural and an anthropogenic component. The value of the technique lies primarily in determining the spatial distribution and temporal variability of air-sea CO_2 fluxes. It is particularly useful where the signals are large,as in the North Atlantic and Equatorial Pacific,or in the contrast between El Niño and non–El Niño years.

One currently weak link in the air-sea CO_2 flux approach is poor understanding of the kinetics of the process of air-sea gas exchange (see Wanninkhof 1992). The degree of nonlinearity in the relationship between the gas-exchange and wind speed is poorly understood,particularly at high wind speeds where bubble effects may become important. For instance, if the exchange velocity were to depend more strongly than is currently believed on variables correlated with wind speed, our estimates of fluxes in regions with high wind speeds, such as the high latitudes, would increase. It is time to determine through measurements a much better parameterization of the exchange velocity, so that observations of the atmosphere can be truly informative for oceanographic issues, and vice versa. Surface sources and sinks drive large-scale gradients of atmospheric CO_2 concentrations that could be, for example, an important constraint on CO_2 uptake by the Southern Hemisphere ocean poleward of about 30°S. As atmospheric transport models continue to improve,this constraint will become more compelling as a major input for inverse models of atmospheric CO_2 observations.

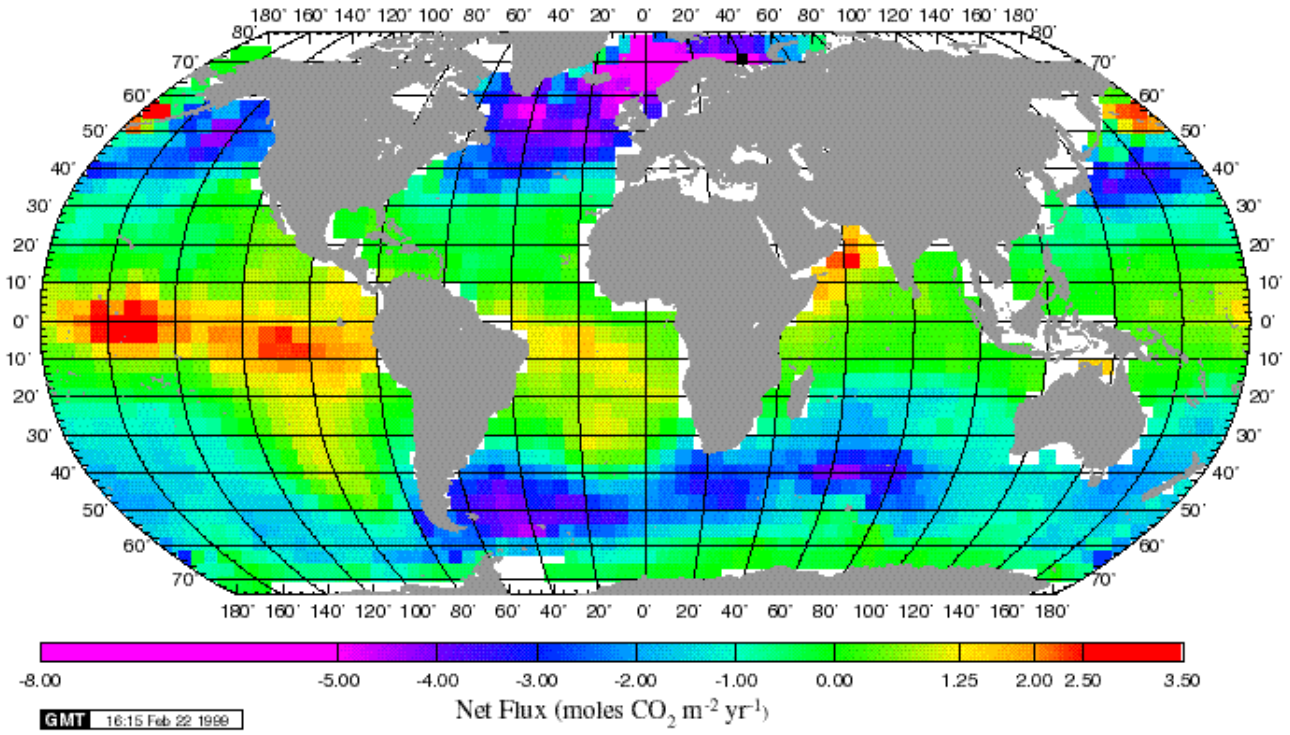
Another analysis approach that makes use of oceanic DIC data is estimation of horizontal carbon transport within and between ocean basins (e.g.,Brewer et al.1989, Holfort et al.1998). This approach permits separate assessments of the transport of natural and anthropogenic carbon components in the ocean. The air-sea flux can be inferred from the divergence of the horizontal transport, which would provide a means of coupling the ocean inventory method with the surface ΔpCO_2 method. While horizontal carbon transport estimation is only starting to be implemented in the ocean,the tremendous improvement in ocean DIC measurements and the large new data set gathered by WOCE/JGOFS show great promise for the near future.

Knowledge of the spatial distribution of the air-sea CO_2 flux varies greatly from one region to another. The North Atlantic is perhaps the best-constrained region. Models, observation-based estimates of air-sea flux,and estimates of the ocean inventory of anthropogenic carbon all converge on similar answers (Gruber 1998,Gruber et al. 1996,Sarmiento et al.1995,Takahashi et al.1997). However, difficulties remain in reconciling these estimates with independent estimates of the net meridional transports of carbon (Brewer et al.1989;Broecker and Peng 1992;Holfort et al.1998, Keeling and Peng 1995). The North and Equatorial Pacific Ocean have not been as thoroughly explored,though the measurements that are available show reasonable consistency. The rest of the world is mostly very poorly constrained.

Analysis of CO_2 exchange in the Southern Ocean Ocean (waters around Antarctica poleward of approximately 50°S latitude) is especially difficult because of the high spatial and temporal variability of its properties and the difficulty of working in that region. The Southern Ocean appears to be especially important to levels of atmospheric CO_2. Deep ocean waters are mixed to shallow depths there,providing one of the major pathways for the uptake of anthropogenic CO_2 into the deep ocean. Wind speeds are high,enhancing rates of air-sea CO_2 exchange. The dissolved macronutrients available at the surface for plant growth are significantly underutilized (e.g., Falkowski et al.1998),suggesting a capacity for enhanced uptake of CO_2 by photosynthesis. Macronutrients may be underutilized for several reasons;there is less sunlight at high latitudes,biological processes are slower because of low temperatures,there is less time for biota to develop because surface water is mixed back into deeper layers more quickly, and necessary micronutrients such as iron may be less available (Baar et al.1995, Falkowski 1995). All these factors may be affected by climate change.

Models of the oceanic uptake of anthropogenic CO_2 (e.g.,Sarmiento et al.1992) predict that a substantial amount is being absorbed south of 30°S. Yet there are large discrepancies between the observations and the models of oceanic CO_2 uptake in the high southern latitudes. Recent survey data for the southern Atlantic (Gruber 1998) and Indian (Sabine 1999) oceans show surprisingly little uptake in these areas. The (sparse) atmospheric data also point toward a small Southern Ocean sink. Recently, observations of a composite atmospheric tracer, effectively equal to the sum of atmospheric O_2 and CO_2 concentrations, were compared with predictions from three different ocean models (Stephens et al.1998). The largest discrepancy between models and observations was found over the Southern Oceans,suggesting that the models may misrepresent exchanges of O_2 and CO_2 in this region.

There are few constraints on the temporal variability of the air-sea flux of CO_2. The Equatorial Pacific is being monitored reasonably well (e.g., Feely et al.1995, Feely



Distribution of the mean annual sea-air pCO_2 flux (partial pressure of carbon dioxide, moles $CO_2/m^2/yr$) over the global oceans estimated for a reference year 1995. These data show the global pattern of surface CO_2 uptake and release by the ocean. Note that the major sink regions are the North Atlantic and Southern Oceans, and that the Equatorial Pacific is a large source region in a typical year. This map does not reflect the variability due to El Niño/Southern Oscillation (ENSO) cycles, for example, which can alter the size of the ocean sink on an interannual basis. This map has been constructed based on about 2 million measurements of sea-air pCO_2 difference made over the past 25 years. These values have been corrected to a reference year of 1995 for the increase in pCO_2 of the atmosphere and surface ocean water that has occurred since the measurements were made, and the measurements made during El Niño years in the equatorial Pacific have been excluded. Thus, the map represents a climatological mean for non-El Niño conditions. The net CO_2 flux across the sea surface has been computed using the effect of wind speed on the CO_2 gas transfer coefficient formulation by Wanninkhof (Equation 1, 1992) and the mean monthly wind speed of Esbensen and Kushnir (1981). The numerical method used for the construction of these maps has been described in Takahashi et al.(1997) and Takahashi et al.(in press). The map yields an annual CO_2 flux for the oceans of 2.2 PgC/yr, in which the North Atlantic (N of 14°N) and the Southern Ocean (S of 50°S) are major CO_2 sink areas taking up 0.8 and 0.6 PgC/yr respectively.

et al.1994, Feely et al.1996),and the ongoing feasibility studies to instrument the ATLAS moorings of the Tropical-Atmosphere-Ocean (TAO) array with CO_2 sensors are an important development (Friederich et al.1995). There are also two time-series measurements near Bermuda and Hawaii (e.g.,Bates et al.1996, Winn et al.1994). However, most of the ocean is unknown with regard to the temporal variability of CO_2 fluxes. Analyses of stable carbon isotopes in atmospheric CO_2 suggest that sinks in both the ocean and the terrestrial biosphere vary by large amounts from year to year (Keeling et al.1989, Keeling et al.1995a, Ciais et al.1995b, Francey et al.1995). No oceanic mechanism has been developed to explain such conspicuous variability. A related need is for the calculation of temporal changes in oceanic carbon uptake on the global scale. The global oceanic uptake rate of CO_2 is currently not known to better than about ± 40 percent. This knowledge is not sufficient to determine whether the ocean carbon uptake rate has increased or decreased over the past few decades. Moreover, uncertainties of this magnitude limit the ability to constrain the historical global CO_2 budget using the record of atmospheric CO_2 concentrations over the last 200 years.

However, the problem of understanding the ocean should not be viewed as simply a comparison of current and future DIC "snapshots." It is also important to identify and understand the mechanisms that might cause future changes in the ocean carbon sink.

One of the most important issues to address is which mechanisms of ocean circulation that significantly shape anthropogenic CO_2 uptake are likely to be affected by a changing climate?

Changes in ocean circulation resulting from climate change will immediately affect the way anthropogenic

CO_2 is exchanged between the atmosphere and the ocean. The behavior of the present and past ocean, including the response to temporal variability, provides the strongest clues to the links between ocean circulation and atmospheric CO_2.

An additional question is how is the biological pump affected by the thermohaline circulation and changing climate? And is there any evidence that the C/N and C/P ratios of marine production are changing,or that "preformed" nutrients (the nutrient concentration of water that has cooled and sunk to depth) are changing?

CO_2 exchange between the ocean and atmosphere naturally occurs at the ocean surface. Photosynthesis by organisms in the upper, sunlit layer of the ocean keeps the CO_2 concentration of the surface waters substantially lower than that of deep waters. It does so by producing organic carbon that is exported to the deep ocean where it is converted to DIC. The excess deep ocean DIC that thus results is analogous to the organic carbon stored in soils, in that it is isolated from the atmosphere. Without photosynthesis in the ocean, and assuming no other surface changes due to organisms (such as calcification),the excess deep ocean DIC would escape to the atmosphere and atmospheric CO_2 concentration would be between 900 and 1,000 ppm (the current value, again, is 365 ppm). If, on the other hand, photosynthesis continued everywhere until all of the plant nutrients were fully depleted in all surface waters,atmospheric CO_2 would be between 110 and 140 ppm. (The actual pre-industrial atmospheric CO_2 concentration was 280 ppm.) These figures indicate the great power of the oceanic biological pump.

Long-term surface ocean time series that include detailed biogeochemical and CO_2 measurements are improving the mechanistic understanding of processes that affect ocean-atmosphere carbon uptake and partitioning. Time-series data sets from Bermuda and Hawaii are being used to develop model parameterizations of ocean biogeochemical processes affecting the ocean carbon cycle (Doney et al. 1996, Fasham 1995). Such time series are also increasingly being used as test beds for novel high-resolution measurement instruments. Notable findings from the time-series sites include an increased awareness of the complexity of the ocean's nitrogen cycle (Karl et al. 1997). This finding has the potential to alter the view of the sensitivity of atmospheric CO_2 concentrations to biological processes in the ocean (Falkowski 1997). On longer time scales, ocean biology can have an impact on the atmosphere (see the following chapter). The time-series sites are among the few locations where seasonal variations in upper ocean $^{13}C/^{12}C$ ratios are measured (Bacastow and Keeling 1973). Such time-resolved information is critical for correctly interpreting the large "snapshot" data sets collected along ocean transects.

To summarize, our current understanding is that, as atmospheric CO_2 levels increase through time, the ocean responds by dissolving more CO_2 in the surface mixed layer, and by mixing the CO_2-enriched surface waters downward through exchange with deeper waters. The possibility also exists that changes in the biological pump may affect the future air-sea balance of CO_2. If our present understanding of these processes is correct,the ocean should have the capacity to absorb large quantities of anthropogenic CO_2 over time scales of decades to millennia. Most model simulations of future atmospheric CO_2 levels assume that present-day factors controlling plant physiology, air-sea exchange, and ocean mixing will remain constant into the future (Schimel et al. 1996). However, as previously noted, these assumptions have been questioned, especially because of the potential for significant responses to climate change. Air-sea gas exchange, ocean circulation, and marine photosynthesis are susceptible to changes in air temperatures,wind velocities, sea surface roughness, and wind and precipitation patterns. The most powerful tool for understanding the mechanisms underlying potential changes is in studying long-term trends and shorter-term fluctuations. Given all these considerations, a major CCSP initiative in ocean carbon cycle research is proposed to achieve the following:

Goal 2: Establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it.

Land Use

One of the main driving factors in determining the Northern Land Sink may be land use,both past and present. For example,there has been widespread reforestation since 1900 in the eastern United States following the movement of the center of agricultural production toward the Midwest. Also,less agricultural land is needed today than during the first half of this century;the productivity of agriculture has improved so much that double the output can be produced on half as much land. The heavy use of fertilizer, together with improved tilling practices,may also lead to increased stores of organic matter in soils.

The carbon balance in the tropics also affects estimates of the magnitude of the Northern Land Sink. As pointed out before,the major constraint on the estimated magnitude of the global terrestrial carbon sink comes from two numbers. The first is the estimate of a global net terrestrial uptake of 0.2 ± 0.9 Gt C/yr for the period from 1980 to 1989. This number is obtained from calculating fossil fuel

***Top panel**: Managed forests in the Coast Range of Oregon. Conversion of old-growth forests to managed plantations in the Pacific Northwest has reduced the store of carbon to less than 25-35% of the maximum value in the last century. This has resulted in a substantial loss of carbon to the atmosphere. Altering management by increasing the interval between harvests and/or removing less carbon each harvest would "re-store" much of this carbon over the next century.*

***Bottom panel**: Deforestation in tropical regions has released a substantial amount of carbon in the last 50 years. Here the moist tropical forest of Los Tuxlas in Veracruz State, Mexico has been converted to maize and pasture agriculture. This conversion has reduced carbon stores on these sites at least 5-fold.*

emissions minus atmospheric growth and ocean uptake. The second number is the estimate of 1.6 ± 1.0 Gt C/yr released to the atmosphere from tropical deforestation. The difference between these numbers gives a required terrestrial uptake of 1.8 ± 1.4 Gt C/yr (Schimel et al. 1996), much of which appears to be in the Northern Hemisphere. If the net carbon flux from changes in tropical land use were at the lower limit of 0.6 Gt C/yr, the Northern Land Sink would drop to 0.8 Gt C/yr. Maintaining the observed north-south gradient of CO_2 in the atmosphere would require that the Southern Ocean would have to be a smaller sink than currently estimated. The recent land use estimate of Houghton et al.(1998) yields 2.0 ± 0.8 Gt C/yr for the tropical land use source. This value would require a compensatory terrestrial carbon sink of 2.2 Gt C/yr as well as a larger Southern Ocean carbon sink. Gaining more certainty in the land use numbers will reduce uncertainty in other contributing components of the Northern Land Sink,such as the fertilizing effects of rising atmospheric CO_2 and N deposition.

The uncertainty of net carbon flux from land use stems largely from incomplete and often incompatible databases used to compile land use changes,and from the lack of knowledge of carbon fluxes associated with specific activities. These points are particularly true of tropical areas and for land uses involving economically nonproductive ecosystems (i.e.,nonproductive in a direct sense),such as wetlands, riparian forests,and natural grasslands. For example,Houghton et al.(1998) notes that no reliable data exist for Latin America on that portion of the loss of agricultural land to degraded land that is not recovering to forest. This situation has forced the omission of such land from the calculation of net carbon flux. The same is true for land subjected to shifting cultivation and the harvest of wood in Sub-Saharan Africa.

Tests of the Northern Land Sink hypothesis will thus require the further development and refinement of data sets on historical land use changes,carbon stores per unit area,and models that can use this information. The goal should be to acquire and analyze accurate global inventories of highly fractionated land use change. Doing so, however, requires a concerted effort to develop high-quality, spatially explicit,long-time-series data sets on land use. These data sets should be constructed from a variety of sources,including high-resolution, remotely sensed imagery, explicit data on land use going back many decades, government publications, research data,and reconstruction using proxy information. Side-by-side comparison of population change and measured rates of deforestation,where the data coexist,lends confidence to the reconstruction of rates of deforestation using relatively well-defined changes in population as the predictor.

A major new CCSP initiative is therefore proposed to meet the following goal:

Goal 3: Establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.